ASSESSMENT OF FOOT PROTECTION AGAINST ANTI-PERSONNEL LANDMINE BLAST USING A FRANGIBLE SURROGATE LEG

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Abstract

Anti-personnel (AP) landmines pose a threat to soldiers and civilian populations and have come into the focus of the international community. The purpose of our study was to assess the performance of various types of footwear against the blast effects of AP landmines on the lower leg using a Frangible Surrogate Leg (FSL). The FSL is an anthropomorphic model of the lower extremity from the proximal femur to the foot. The FSL consists of anatomically correct bones constructed from Computerised Axial Tomography (CT) images, with synthetic knee and ankle ligaments that are encased in a "soft tissue" envelope made of ballistic gelatine. Load cells and strain gauges placed on the tibia and foot measured the biomechanical parameters imposed by the blast. Radiographs, CT and clinical dissection by medical staff were performed on each FSL following the tests.

The FSL performed well and produced consistent results from test to test. Although the FSL soft tissues did not accurately reproduce vascular and nerve details, the extent of bone injury was used to develop a correlation to bone and soft tissue damage observed during human cadavers trials under the US Lower Extremity Assessment Program (LEAP). Based on the Mine Trauma Score (MTS from LEAP), the extent of gross damage to the bones provided some correlation with the human cadaver data. This allowed an objective evaluation of the protective performance for a range of footwear against landmines that contained from 35 grams up to 100 grams of high explosive. Some footwear was effective at preventing or, at least reducing, the severity of injury.

Introduction

Personnel engaged in humanitarian demining and soldiers participating in peace keeping missions face the hazard of injury from AP landmines. These weapons are classified in two families as a function of their primary injury-producing mechanism, fragmentation or blast. This study focuses on blast landmines. A survey of 232 landmine accidents that injured 295 victims [1] during humanitarian demining operations indicates that injuries to the lower extremities are frequent. It is reported that 186 of the 295 victims received injuries to one or both legs and that an AP blast landmine was the cause for 68% of these victims. These statistics provide a clear indication of the relevance of improving the protection of the lower extremities from landmine blast effects.

In order to design better protective equipment, it is first necessary to understand the physical mechanisms during a landmine explosion and the subsequent interaction with the human body. There is a large body of clinical data about the extent of landmine blast injuries and their treatment, but this information is not linked to the threat and environment that prevailed at the time of injury. Thus, there was a need to document the injuries resulting from a landmine blast under controlled conditions. This was the aim of the LEAP [2,3] tests sponsored by the US Humanitarian Demining Program. LEAP developed a database of the injuries inflicted to the lower extremities of human cadavers for a range of footwear and landmine types. This study is particularly useful due to the direct involvement of medical staff working alongside blast physicists and engineers. Information was obtained about the damages to bony and soft tissues.

A study such as LEAP provides a wealth of information. However, testing with human cadavers can only be conducted at specialised institutions and within a strict legal and ethical framework.

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Furthermore, it requires access to medical facilities and staff to fully realise the benefits of the work. Clearly, this class of test methodology is not well suited to the routine testing of protective equipment by manufacturers and industrial or government test agencies. Instead, there is a need for test equipment, test protocols and injury criteria that are tailored to the landmine blast situation, but that do not require the use of biological specimens. Recognising this fact, the Canadian Centre for Mine Action Technologies (CCMAT) sponsored a series of 25 tests [4] with a synthetic surrogate of the human leg that was under development in Australia. These tests were performed at the Defence Research Establishment Suffield in September 1999.

Program Objectives and Scope

The main objective of the CCMAT program is to *develop landmine injury criteria for the FSL so that it can be used in blast tests of protective footwear*. The approach adopted to reach this objective has been through collaboration with the LEAP project team to subject the FSL specimen to the same test conditions as in LEAP. This involved using the same sand, as many of the same landmines as feasible, the same placement of the landmine below the foot, the same footwear, etc. In addition to the primary objective listed above, the CCMAT program addressed a few secondary objectives, which included obtaining relative performance data for a small selection of footwear and assessing the repeatability of the FSL as a diagnostic tool, subject to the inherent scatter of explosive events.

As of September 1999, the FSL was still under development. An early version had been subjected to explosive tests, but there had been no focus to calibrate its mechanical response against landmine injuries to human limbs. The reader must therefore bear in mind that the results presented herein are part of the evolution of the FSL towards validation. However, given that the FSL had reached a certain level of maturity in terms of the quality control of the geometry and materials, it is reasonable to inspect the data for trends. It should also be noted that the medical personnel that assessed the damage to the FSL specimen had previous experience with the treatment of landmine casualties.

Table 1 lists the landmines used during the LEAP and FSL test series. It is seen that only the PMA-2 landmine was common to both test series. The M14 landmine was not available for the FSL tests and the PMA-3 was used instead. The basic footwear used during the FSL tests was the Canadian Forces combat boot and the Wellco blast boot, which is used by the Canadian and US Armies. The latter boot has a composite Kevlar® aramid insole and an aluminium honeycomb blast deflector that is cast in the rubber sole of the boot. The blast deflector runs from the instep to the heel areas. In addition to being used in isolation, each type of footwear was also used in combination with the Wellco overshoe or with the Spider boot®. The design of the sole of the Wellco overshoe is identical to that of their blast boot. The Spider boot® consists of a platform that is supported approximately 100 mm above the ground by four legs that protrude outside of the footprint of the platform. The intent of this design is to intentionally displace the location of the explosion away from the underside of the foot. Table 2 presents the test matrix used during the FSL tests. It gives the number of shots for each combination of footwear versus each type of landmine that was used. It is seen that 10 out of 25 shots were against the PMA-3 while 10 shots were against the PMA-2. The 5 shots with the VS-50 and C4-50 gauged the effect of explosive mass on FSL damages for intermediate mass values between those of the PMA-3 and PMA-2 landmines.

Table 1. *Explosives used during the FSL and LEAP tests.*

Mine	FSL	LEAP	Explosive	Mass (grams)
M14		✔	Tetryl	29
PMA-3	✔		Tetryl	35
VS-50	✔		RDX/TNT	43
C4-50	✔		RDX	50
PMA-2	✔	✔	TNT	100
PMN		✔	TNT	240

Table 2. *Test matrix for the 25 FSL shots.*

		Mine Type			
		PMA-3	*VS-50*	*C4-50*	*PMA-2*
Footwear	*Blast Boot (Wellco)*	1			1
	Combat Boot	1			1
	Blast Boot/Overshoe	2	1		2
	Combat Boot/Overshoe	4	2	2	2
	Blast Boot/Spider Boot				2
	Combat Boot/Spider Boot	2			2

Description of the FSL

The Defence Science & Technology Organisation (DSTO) of Australia developed the Frangible Surrogate Leg. This reproduction of the human lower extremity uses geometrically accurate bones cast from synthetic materials with x-ray visible dye, as shown in Figure 1(a). The bones are assembled using silicone-based materials to represent cartilage while the most critical tendons are simulated using other elastic materials that are glued to the bones at the appropriate anatomical points. The simulated cartilage and tendons are used in the construct of a knee capsule, the ankle joint and in the assembly of the foot bones. The soft tissues are simulated with pig-skin gelatine ($20\%_{aq}$ at 10°C), which is the material that has been in use for several decades as the international standard for the Wound Ballistic community to simulate human soft tissues. Figure 1(b) shows the result of pouring the ballistic gelatine around the bones. As a final step, the skin is simulated with a heavy nylon mesh that is fitted over the leg shape and melted into the outer layer of gelatine. Due to the gelatine, the surrogate legs needed to be kept refrigerated.

The tibia and femur bones of the surrogate legs were instrumented with strain gauges to measure the degree of compressive and bending strain and the shock wave velocity in the bones. In order to obtain data that could be compared directly with the LEAP data, the six-axes load cells that had been used in the LEAP program were installed in eight of the 25 surrogate legs, which were shipped without the outer skin layer. The procedure to install a load cell required removing a portion of the ballistic gelatine to expose the tibia and fibula bones, cutting a pre-determined length of the tibia at the mid-section, gluing receiving cups to the exposed ends of the bone, installing the load cell, pouring melted gelatine back into a leg mould and letting it cure overnight.

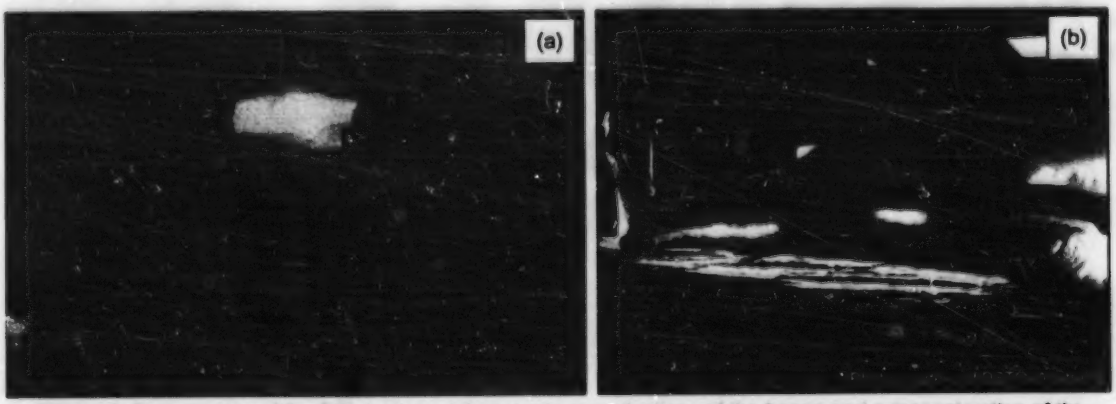

Figure 1. *Components of the FSL include: (a) accurate reproductions of the bones and a reconstruction of the knee and ankle joints and with strain gauges and (b) bones enclosed in gelatine.*

Test Procedures

Figure 2 shows the experimental setup that was used in support of the FSL tests. It consisted of a wooden platform with an overhead support beam to bring the instrumentation cables vertically above the surrogate leg and away from the blast zone. The surrogate legs supported their own weight with the exception of a small percentage taken by the tension of the four guy-wires that were used to stabilise and hold each surrogate leg in the vertical position. A steel box with dimensions 610 mm × 457 mm and 457 mm deep was located at the centre of the platform. The box was identical to that used during the LEAP tests and was filled with dry sand. The sand also matched closely the sand used during the LEAP tests. It should be noted that since the FSL does not pose a biohazard, the test layout was fully open to the outdoors. As a result, each test was followed by a period of combing the surrounding area for pieces of boot, overboot and surrogate leg fragments. This meant that numerous fragments were not recovered.

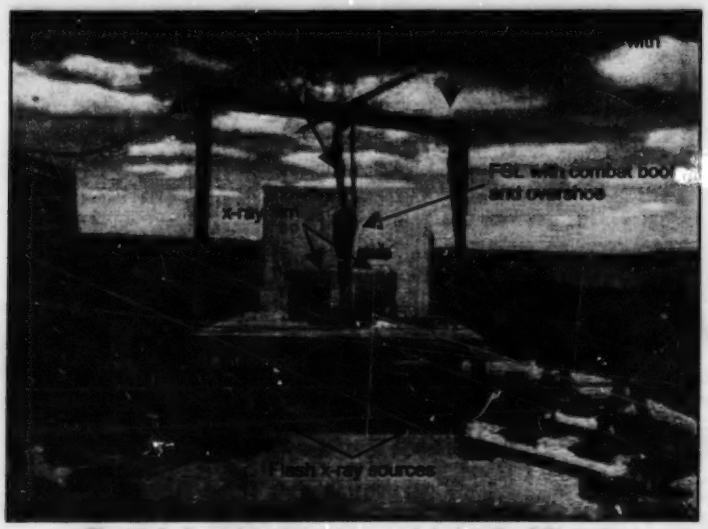

***Figure 2.** Experimental setup used during the FSL tests.*

As with the LEAP tests, the landmines were placed at the centre of the sand box and buried flush to the surface, with the exception of the PMA-2, which was buried to the depth that placed its star-shaped plunger slightly proud of the surface as in a real deployment. For all shots with the basic footwear with and without the overshoe, the surrogate leg was positioned such that the heel of the foot was centred above the centre of the landmine. For the shots against the Spider boot, the surrogate leg was located such that a front or rear leg of the Spider boot was centred above the centre of the landmine. Hence, for the Spider boot shots, the surrogate leg was offset from the direct vertical path of the blast above the landmine.

Once the landmine had been buried and the surrogate leg placed in position, final checks were carried out to ensure that the instrumentation was functional. In addition to the strain gauge and load cell data, the flash x-ray film cassettes were put in place and the system set ready. The orientation of the flash x-ray heads, as shown in Figure 3, allowed the acquisition of a medial and a lateral view of the surrogate leg. These views were preferred over two diagonal views because it greatly improved the quality of the lateral image. The delays used for the x-ray heads varied from 500 to 1250 microseconds after detonation. High-speed video was also used during these tests with a framing rate of 1000 frames per second.

Following each test, the damaged leg specimens were photographed and returned to refrigerated storage. At the end of each trial day, the test specimens were then brought to a local hospital where medical x-rays and Computerised Tomography scans were taken. A radiologist inspected the x-rays and produced a diagnosis. The surrogate legs were then subjected to dissection for closer inspection by a team of surgeons. The damages recorded were then given a score in accordance with the Mine Trauma Score (MTS) that was developed during the LEAP program. Table 3 gives a description of the MTS, which is based on the final medical outcome in regards to the level of amputation that is likely required to treat the patient. The surgeons were blind to the type of landmine and footwear that had been used for the tests.

Table 3. Definitions of the Mine Trauma Score (MTS).

Score	Injury	Level of amputation required
0	Minimal	No major surgery required
1	Closed	Salvageable limb
1A	Open contained	
1B	Open contaminated	
2	Closed	Below knee amputation
2A	Open contained	
2B	Open contaminated	
3	Open contaminated	Below or above knee amputation
4	Open contaminated	Above knee amputation

Closed injury: any injury that does not violate the skin and for which there is minimal risk of infection.

Open contained: any injury that violates (lacerations, tears) the skin, but that is not contaminated by environmental debris because the inner footwear was not compromised.

Open contaminated: any injury that violates the skin and that is contaminated by environmental debris.

Test Results

The blast from an AP landmine under a minimally protected foot has disastrous consequences. Figure 3 depicts the typical result from the explosion of a small AP landmine (PMA-3) under the heel of a blast boot. It is seen that there is severe disruption of the boot in the proximity of the blast that destroyed part of the upper covering, and that a portion of the sole near the heel is missing. In addition, the metal blast deflector in the sole was crushed and severely bent out of shape. The damages to the boot left an open path for entry of environmental contamination in the wound. It is also seen that the blast was of sufficient strength to cause traumatic amputation of the foot from the lower leg above the ankle joint.

Adding the overshoe over the inner boot improves the situation for small blast landmines. It is seen in Figure 4(a) that the overshoe prevented the traumatic amputation of the foot during the blast of a PMA-3 landmine. The external damage appears to be limited to the heel portion of the overshoe. However, Figure 5(a) reveals that the blast imparted a significant amount of internal damage to the bones of the surrogate leg. Multiple fractures of the tibia and fibula bones can be seen along with a dislocation of the ankle joint. It is noted that the calcaneus bone was intact, which is contrary to the observations made during LEAP. It was found later that the strength of the calcaneus for these surrogate legs was too high. The post-test examination also revealed that there had been considerable disruption of the soft tissues in the rear foot region.

***Figure 3.** Damage to blast boot and leg from PMA-3.*

The extent of external and internal damage to the surrogate legs increased with the mass of explosive in the landmines. Figures 4(b) and 5(b) show the results for a surrogate landmine charge with 50 grams of C4 explosive. For this mass of explosive, the overshoe was destroyed and separated from the inner boot. The external envelope of the inner boot was also breached. Although the foot appeared to remain attached to the leg, there had in fact been a traumatic amputation of the foot with significant bone loss. Internally, there were multiple fractures of the tibia and fibula with dislocation and displacement of the anklebones. Environmental and boot debris was contaminating the wound.

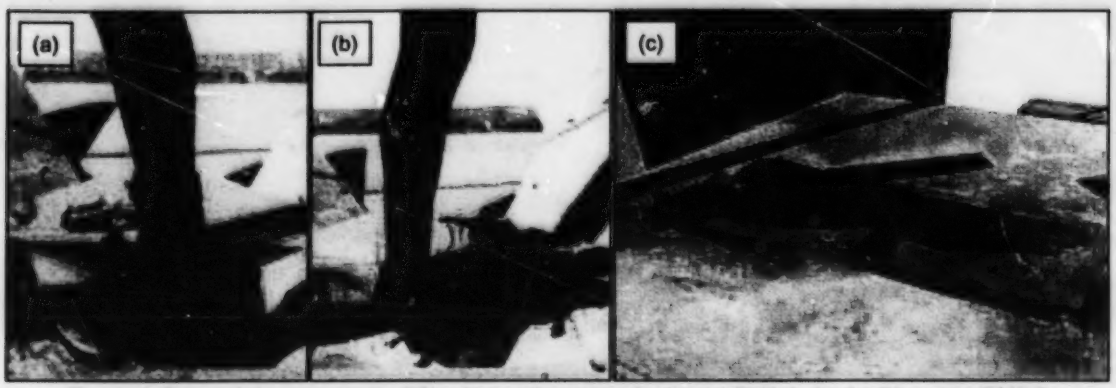

Figure 4. External damages to the FSL with boot/overshoe for the (a) PMA-3, (b) C4-50 and (c) PMA-2.

Increasing the explosive mass further to the PMA-2 level resulted in a traumatic amputation with complete separation of the foot from the lower leg, as seen in Figure 4(c). The overshoe was destroyed and the inner boot was breached. A substantial portion or the foot remained in the boot. Figure 5(c) shows that this amount of explosive also resulted in breaks of the tibia and fibula bones, but it appears that the greater amount of explosive resulted in a cleaner break of the lower leg than for the lesser charge of 50 grams of C4. On the other hand, there was severe environmental contamination of the soft tissues up to the proximal 1/3rd of the tibia.

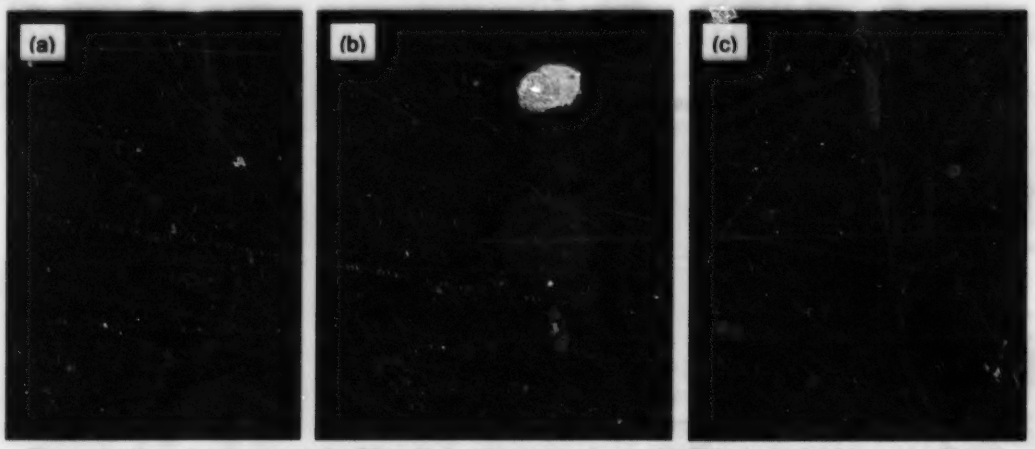

Figure 5. Internal damages to the FSL with boot/overshoe for the (a) PMA-3, (b) C4-50 and (c) PMA-2.

Figures 6 and 7 compare the MTS scores from the FSL and LEAP test series for the M14 and PMA-3 landmines without and with overshoe, respectively. This provides a measure of the value of using a frangible surrogate leg to assess the level of amputation following the explosion of an AP blast landmine under the foot. The reader is reminded that the PMA-3 was used during the FSL tests. This landmine contains 20% more explosive that the M14 that was used during the LEAP tests. In spite of this difference, it is seen that there is good correlation of the MTS scores from these two different test series.

Figure 6 indicates that the MTS scores were worse during the LEAP tests than during the FSL tests despite using the smaller M14 landmine. This higher level of amputation is mainly due to severe environmental contamination of the soft tissues. The contamination was driven in up to the level of the knee by the force of the blast, which would require an above-knee amputation. In comparison, the soft tissues of the FSL differ considerably from human muscle tissues. The former consists of a near homogeneous gelatinous medium while human tissues are fibrous with their long-axis roughly aligned with the direction of the flow generated by the landmine blast.

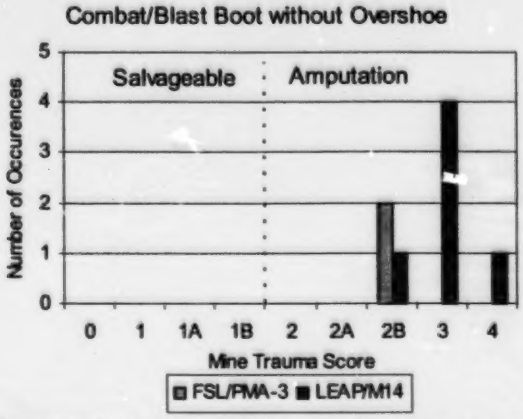

Figure 6. FSL/LEAP results for combat/blast boot without overshoe versus M14/PMA-3 mines.

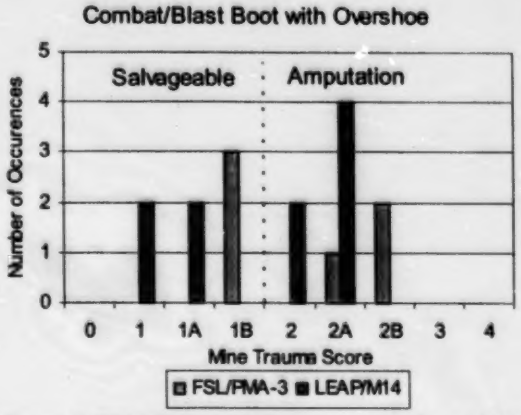

Figure 7. FSL/LEAP results for combat/blast boot with overshoe versus M14/PMA-3 mines.

Figure 7 supports the previous observation that use of the overshoe helps to reduce the level of the amputation for the smaller landmines. No above-knee amputation was diagnosed during both the LEAP and FSL tests. In fact, there were several cases where the injury would be salvageable because the additional protective layer reduced the level of environmental contamination of the wound. The data also indicates the presence of a bias between the LEAP and FSL results. The two factors that may have caused this bias are the greater mass of explosive in the PMA-3 and the greater strength of the calcaneus bone in the FSL as compared to the human calcaneus. The latter factor increases the load transfer higher up the leg and likely causes artificial fractures in the FSL that would not otherwise happen in the human anatomy.

Figure 8 shows the MTS scores for the FSL and LEAP tests when the PMA-2 landmine was used against a basic inner boot with the overshoe. It is seen that the greater explosive content results in higher amputation levels. The data indicates that for this particular combination of protective footwear and landmine, the FSL and LEAP results are similar. Since the injuries from this combination are open contaminated, the previous comments about the structural differences in the soft tissues composition of the FSL relative to the human soft tissues also apply here.

The results from Figure 9 require reflection about the mechanism of landmine blast trauma to the lower extremities. It is seen that the Spider boot resulted in a significant decrease of the level of amputation. For all cases where the landmine was detonated under one of the supporting legs, the MTS score indicated that the limb would be salvageable. The two cases with a 2A score, i.e.,

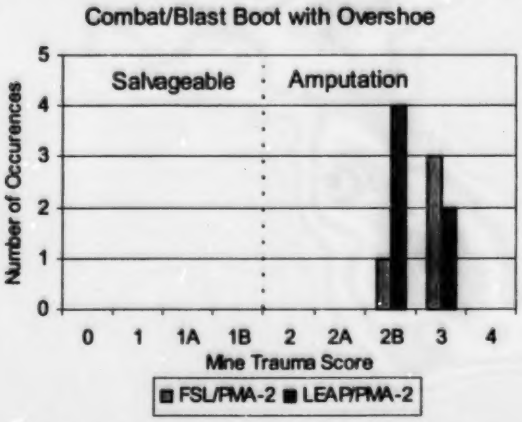

Figure 8. FSL/LEAP results for combat/blast boot with overshoe versus PMA-2 mine.

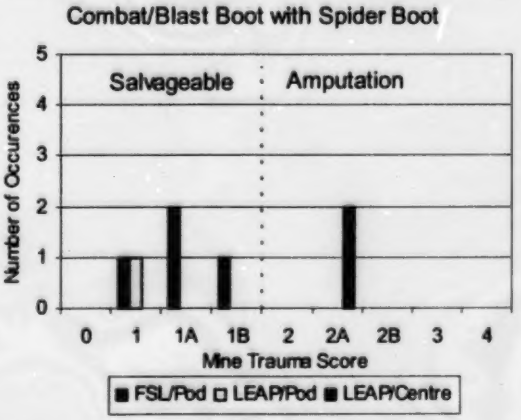

Figure 9. FSL/LEAP results for combat/blast boot with Spider boot versus PMA-2/PMN mines.

a below-knee amputation, were respectively for the explosion of a PMA-2 and a PMN landmine under the centre of the platform of the Spider boot. This is a worst case situation. It should be noted that even for these conditions, the injuries consisted of multiple bone fractures in the lower and the ankle. The calcaneus was also fractured in each case, indicating that the platform of the Spider boot was driven upward against the lower extremity. Considering that the detonation of the same landmines under the boot/overshoe combination resulted in amputations higher up the leg, it is believed that the additional standoff and greater venting provided by the Spider boot were key factors to reduce the level of injury to the lower extremity.

Conclusions

The initial FSL test series went a long way towards meeting the main objective of the program. The consistency of the results and relatively good correlation with the LEAP data indicate that the FSL can be developed into a practical tool to assess the performance of protective footwear against the blast of AP landmines. It is noteworthy that the good correlation was obtained in spite of differences in the fracture pattern between the FSL and LEAP results and in spite of the low fidelity of the FSL simulant for soft tissues. It was also clear from the results that the strength of the calcaneus and talus bones needed to be reduced to improve the fidelity of the FSL.

The results from these tests confirm that the medical outcome of a landmine blast under a foot depends on the combination of footwear and explosive mass. The shots against unprotected footwear or the conventional blast boot alone resulted in traumatic amputation even for the smallest landmine used. The addition of a protective overshoe improves the medical outcome for the smaller mine, but this is rapidly negated by an increase of the explosive mass. The Spider boot approach appears to provide a substantial improvement of the protection, as it resulted in a large number of salvageable limbs when the detonation occurred under one of the legs extending outside of the projection of the platform. It is believed that the combination of standoff, venting and the displacement of the point of explosion all contributed to the reduction of the level of amputation for this particular footwear.

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